Failures in Hybrid Microcircuits during Environmental Testing. History cases.

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Purpose and Outline

Purpose:

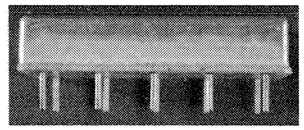
To discuss failures in hermetic hybrids observed at the GSFC PA Lab. during environmental stress testing.

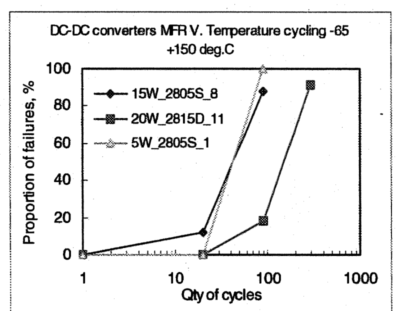
Outline:

- ❑ Case I. Substrate metallization failures during TC.
- ❑ Case II. Flex lid-induced failure.
- ❑ Case III. Hermeticity failures during TC.
- ❑ Case IV. Die metallization cracking during TC.
- ❑ How many test cycles and parts is necessary?
- ❑ Case V. WB failures after life test.
- ❑ Case VI. Failures caused by Au/In IMC growth.
- ❑ Conclusion.

Case I. Substrate Metallization Failures during Temperature Cycling

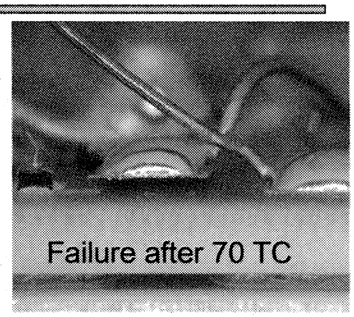
- Hybrid DC-DC converters (5W to 20W) manufactured by different vendors were tested at -55, +25, and +125 °C after 20, 100, 300, and 1000 TC from -65 °C to +150 °C.
- Failures in parts manufactured by one vendor were observed starting 20 TC.
- Out of 20 tested parts 17 parts failed after 300 TC.
- Most parts failed at RT and 23% failed at -55 °C.

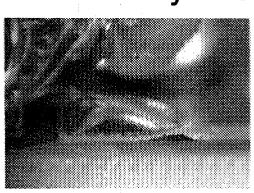


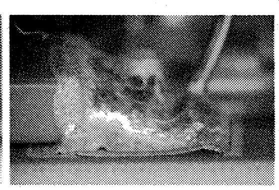


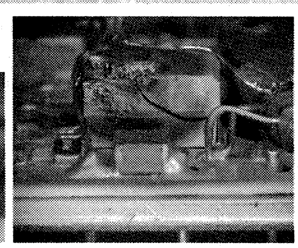
Case I. Results of Failure Analysis.

- Most failures were due to fractured metallization traces on the substrate near solder joints.
- Element and components are evaluated per MIL-PRF-38534.
- Failed Ta capacitor was observed in two cases.
- Capacitor failures might be caused by intermittent contacts.

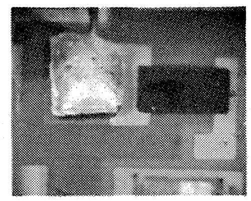








Case I. Deficiencies of Substrate Qualification per MIL-PRF-38534.



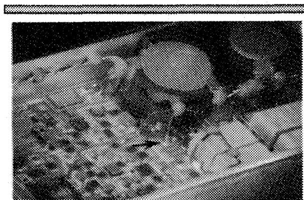
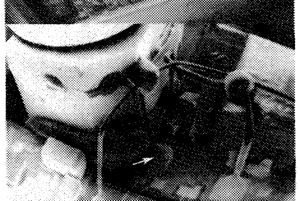
- C.3.7… Substrates fabricated …using a qualified process will be exempt from this evaluation.
- C.3.7.5.2.3… Perform film adhesion testing per acceptable industry standards.
- C.3.7.5.2.4… Perform solderability testing if specified in the applicable specification. (The test does not assess the effect of soldering on metallization).

TABLE C-V. Substrate evaluation requirements.

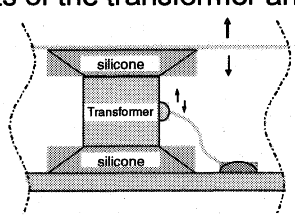
Subgroup	Class K	Class H	Test	MIL-STD-883 Method	Quantity (accept number)	Reference paragraph
1	X	X	Electrical testing		100 percent	C.3.7.3
2	X	X	Visual inspection	2032	100 percent	C.3.7.4
3	X	X	Physical dimensions	2016	5(0)	C.3.7.5.1.1
	X	X	Visual inspection	2032		C.3.7.5.1.2
	X	X	Electrical			C.3.7.5.1.3
4	X	X	Conductor thickness or conductor resistivity		3(0)	C.3.7.5.2.1 C.3.7.5.2.2
	X	X	Film adhesion test			C.3.7.5.2.3
	X	X	Solderability			C.3.7.5.2.4
5	X	X	TCR		2(0)	C.3.7.5.3.1
	X	X	Wire bond evaluation	2011	10(0) wires or 20(1) wires	C.3.7.5.3.2
	X	X	Die shear evaluation	2019	2(0)	C.3.7.5.3.3

Existing requirements do not address effects of soldering and TC on reliability of metallization.

Case II. Flex-Lid-Induced Failures.

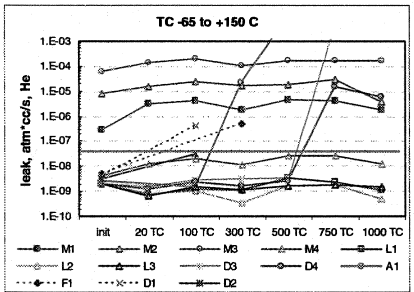




- A DC-DC converter failed during box-level testing in a thermo-vacuum chamber.
- The failure was due to a soldered joint fracture.
- Failed wire was secured to the transformer fixed to the lid with silicone.
- Mechanism of failure: low-cycling fatigue caused by deformation of the lid and shifts of the transformer and wire.

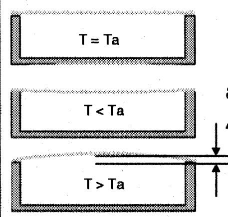


Case III. Hermeticity Failures during TC.

Variations of the Leak Rate with TC



- MIL-PRF-38534 requires 3(0) after 15 TS -65 to +150 °C for package seal evaluation.
- 5 out of 31 hybrids failed after 100 TC -65 to +150 °C.
- "Leaky" hybrids do not fail: $\tau = P_0 V/L$.



$$\Delta P = P_0 \frac{\Delta T}{T_0}$$

at $\Delta T = 215\ ^{\circ}C$
$\Delta P = 0.72$ atm

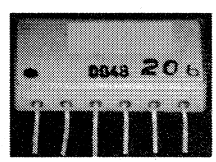
For a disc lid: $$\delta = \frac{pR^4}{64D}$$

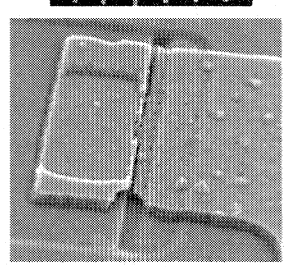
$D = E \times h^3/[12(1-\mu^2)]$ is lid rigidity.
At h = 0.38 mm and R=15 mm
$\delta = 60\ \mu m$.

Large-size hybrids might be more susceptible to hermeticity failures

Case IV. Die Metallization Failure during TC.

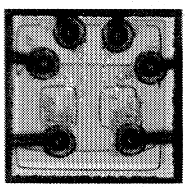
- DPA has indicated a poor die metallization step coverage.
- Thinning of die metallization is typically considered as a reliability risk due to increased current density and possibility of electromigration failures.
- The parts passed life testing, but one out of 7 hybrids failed after 300 TC between -65 °C and +150 °C.

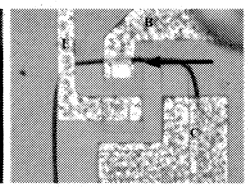


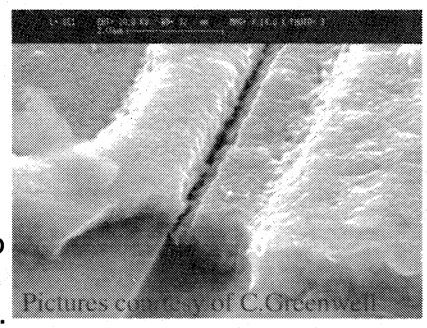


Case IV. Results of Failure Analysis.

- The failure was due to open circuit in the base metallization of a transistor.
- Mechanical stresses during TC resulted in low-cycling fatigue cracking of Al metallization and failure of the transistor.







TC can induce enough plastic deformation in the metallization to cause an open circuit failure in case of poor oxide step coverage.

How Many Test Cycles is Necessary?

- MIL-PRF-38534 requires 100 TC between -65 and 150°C, ΔT_{ac} = 215 °C.
- Requirements for space projects differ substantially:
  - During a 2-year geostationary orbit (GEO) mission an instrument might experience ~700 TC between -20 to +40 °C, ΔT_{op} = 60 °C.
  - During a 12-year low earth orbit (LEO) mission parts might be stressed by ~ 70,000 TC between -40 to +60 °C, ΔT_{op} = 100 °C.
- Accelerating factor for TC: $AF = (\Delta T_{ac}/\Delta T_{op})^m$

Typically, for ductile materials *m* varies from 1 to 3, but for brittle materials it can be as high as 6 to 8.

	AF		Required Nc	
m	LEO	GEO	LEO	GEO
2	5	13	15143	55
4	21	165	3276	4
6	99	2117	709	1

100 TC -65 to +150 °C might be excessive for one project and not sufficient for another.

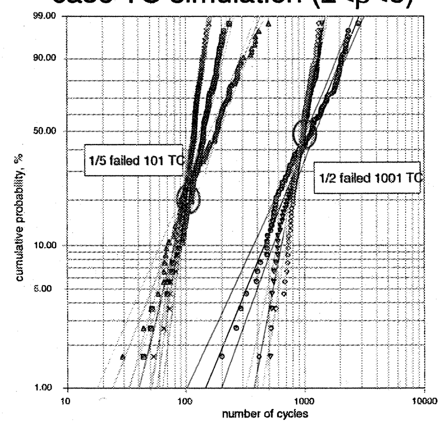
How Many Test Samples is Necessary?

- MIL-PRF-38534 requires testing of 5 parts.
- Space-grade hybrids are expensive ⇨ only a few samples are available.
- Small sample size reduces the confidence in test results.

$$\lambda = \frac{\chi^2(c.l., 2n+2)}{2} \times \frac{1}{AF} \times \frac{1}{N \times M_C}$$

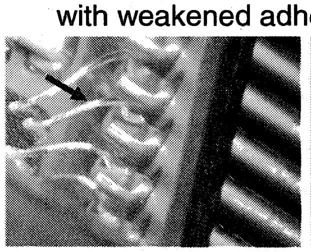
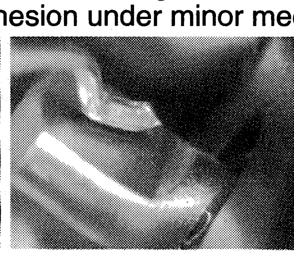
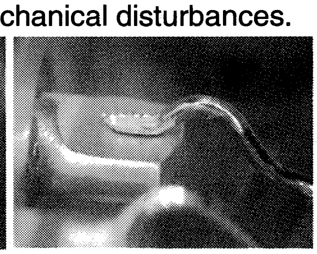
More confidence can be achieved by increasing the number of test cycles.

Weibull distributions of the worst case TC simulation (2<β<6)



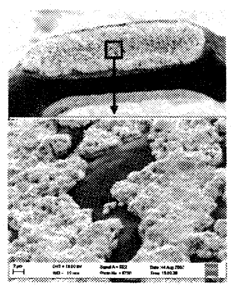
Case V. Wire Bond Failures.

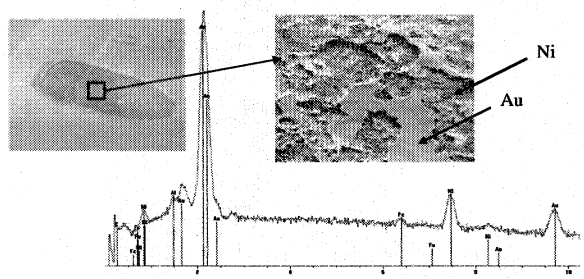
- Five hybrid solid state power controllers successfully passed life testing at 125 °C during 1000 hours.
- Additional electrical measurements after testing unexpectedly revealed open pins in two parts.
- The failures were caused by lifted 10-mil Al wires.
- Although Al wires are annealed, they are stiff and have built-in mechanical stresses, which might result in failures in bonds with weakened adhesion under minor mechanical disturbances.

Case V. Microstructure of Failed Bonds.

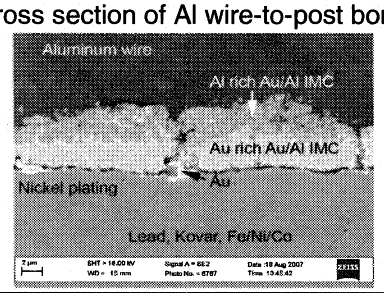
- Failed WBs were separated mostly along the nickel surface exposing relatively minor areas covered by gold.
- Most Au/Al IMC remained attached to Al wires and mating surfaces were ~80% covered with IMC thus indicating that the WBs were formed properly initially.
- No significant amount of contamination was observed during X-ray microanalysis of the failed bonds.

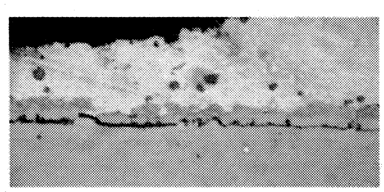




Case V. Mechanism of Failure.

Cross section of Al wire-to-post bond





Purple and tan colors of the Au/Al IMC represent aluminum-rich, $AuAl_2$, and gold-rich, Au_4Al IMC.

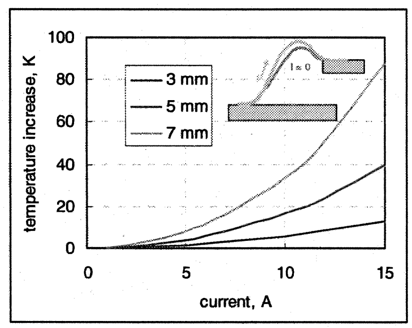
- Formation of Au/Al IMC at the Al/Au interface is a normal phenomenon.
- Au/Al IMC grow with time. At 125 °C all Au plating (~1 μm) is consumed in a few hours and a Ni/IMC contact is formed.
- In the presence of contaminations (Tl, Pb, As) Kirkendall microvoids accumulate resulting in failures (Horsting mechanism).
- Even a very low concentration of contamination (below the level of EDS sensitivity) might be sufficient to cause failures.

Case V. Overheating of Wires.

- In power hybrids the risk of WB failures increases due to self-heating of wires.
- Overheating of wires causes deformation and stress in the bonds.
- Estimations show that for 5 mm long 10-mil Al wire at I = 15 A the temperature might rise on 40 K, which would increase the wire length on ~ 4 μm.
- Power cycling might cause low-cycling fatigue in wire bonds.

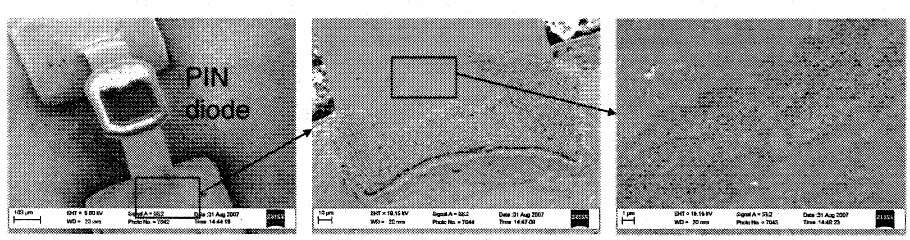
Tmax in wires of different length

$$T_{max} = \frac{1}{\alpha}\left[\frac{1+\alpha T_0}{\cos\left(\frac{l}{2}\sqrt{C}\right)} - 1\right] \qquad C = \frac{I^2 \alpha \rho_0}{\lambda A^2}$$



Case VI. Solder-induced Au/In IMC

- Microwave hybrids passed qualification testing including HTOL at 90 °C for 600 hrs.
- PIN diodes with gold beam leads (170 μm X 5 μm) are installed using an indium-base solder, 80In/15Pb/5Ag.
- To evaluate the effect of In/Au IMC growth on mechanical strength of solder joints, the diodes were pull tested before and after HTS at 125 °C for 110 hrs.



Growth of IMC after 600 hrs at 90 °C occurs by diffusion of Au and In atoms across the thickness of the gold beam lead.

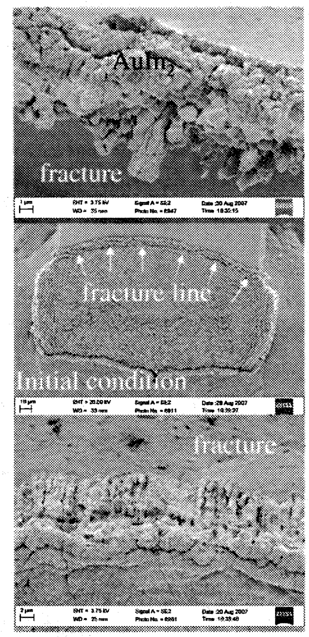
Case VI. Pull Test.

- Fractures occur along IMC growth.
- 3 out of 7 diodes failed after HTOL and 5 out of 7 diodes after HTS.
- The central area of the Au leads was completely converted into a grainy and fragile $AuIn_2$ composition.

Pull test results

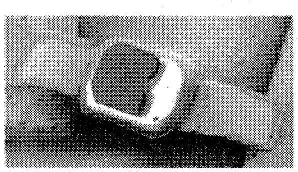
Condition	Part #	D1	D2	D3	D4	D5
After HTOL	16	-	11.8	-	11.7	-
600 hr	17	-	0.9	-	1.6	-
at 90 °C	18	0.24	14	5	-	-
After HTS	16	0.26	-	3.2	-	-
110 hr at	17	0.66	-	2.5	-	0.3
125 °C	18	-	-	-	8	8.3

Note: the calculated strength of the Au beams is ~13 g-f and the failure criteria is 4 g-f.

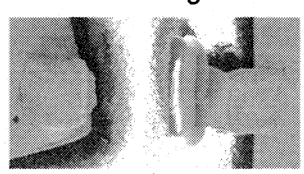


Case VI. Conversion of Entire Lead into Au/In IMC.

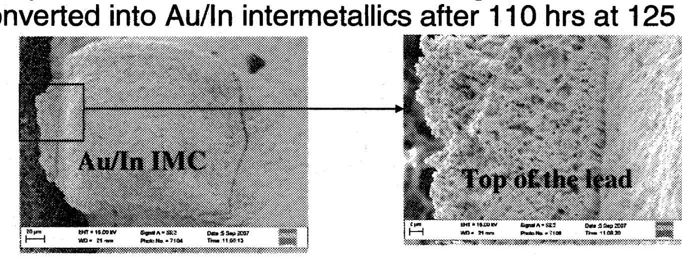
A diode in an initial condition and after HTS testing.



Pull test failure at 0.26g after HTS

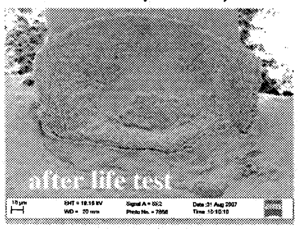


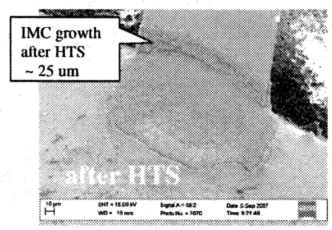
Close-up views of the fractured lead. The gold lead is completely converted into Au/In intermetallics after 110 hrs at 125 °C.



Case VI. The Rate of IMC Growth.

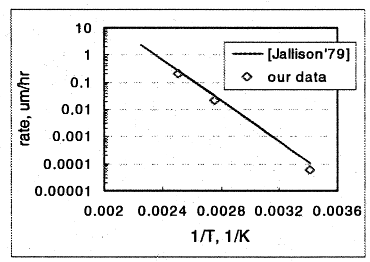
IMC growth on beam leads was estimated at RT, 90 °C, and 125 °C





$$r = \beta \times \exp\left(-\frac{E_a}{kT}\right)$$

For pure Au/In system [Jallison'79]:
β = 6.9E8 µm/hr, Ea = 0.72 eV

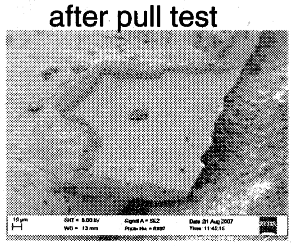


- Results of this experiment (Au - In/Pb/Ag solder) are in agreement with literature data.
- Time to convert a gold beam of a thickness *h* into Au/In IMC is $t = h/2r$. At RT t = 1.6 year.

Case VI. Risk of Failure at Stable Conditions.

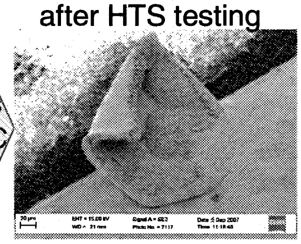
A beam-lead fractured at 11.7 g.

after pull test



Significant deformation is caused by IMC growth

after HTS testing



- Au/In IMC are electrically conductive, but fragile and have reduced strength -> high risk of failure due to TC and/or mechanical disturbances (shock, vibration, etc.)
- A substantial volumetric changes caused by IMC growth (~4X) result in built-in stresses and can cause failures even without external mechanical distortions.

Conclusion

- TC might induce substrate metallization failures. MIL-PRF-38534, substrate evaluation, needs a revision.
- Lid flexibility might cause low-cycling fatigue failures in attached elements and lost of hermeticity.
- Poor metallization step coverage might cause failures due to low-cycling fatigue cracking.
- PoP approach is useful for estimation of TC test conditions.
- Al wire-to-Au-plated-post interconnections might fail due to accelerated IMC growth and microvoiding even at contamination levels below EDS sensitivity.
- To avoid failures in Au/Al interconnections, a highly accelerated aging test per MIL-STD-883, TM 2023 should be performed not only for substrate-to-substrate, but for substrate-to-package WBs as well.
- There is a significant reliability risk in using In-based solder to attach thin Au wires or ribbons. This attachment should be avoided in high-reliability systems.